Cosmic Superstrings & their Astrophysical Consequences

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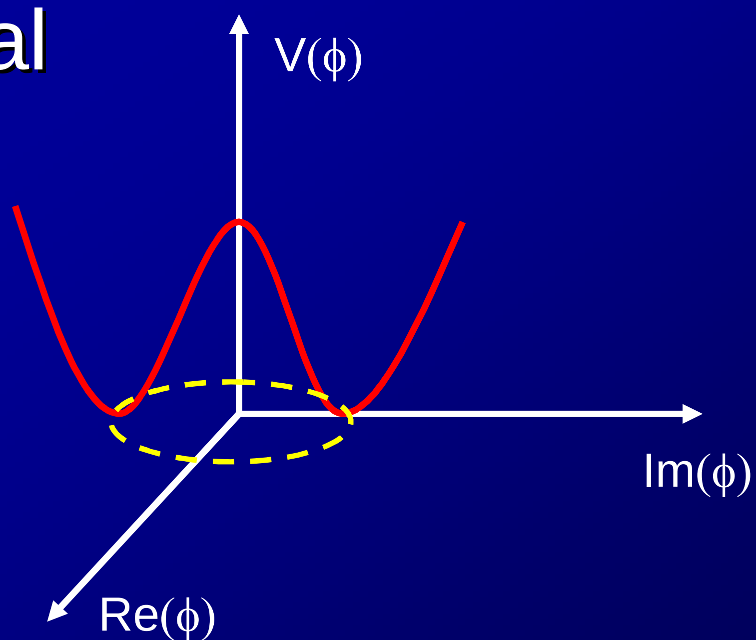
ICCUB

Cosmic Strings

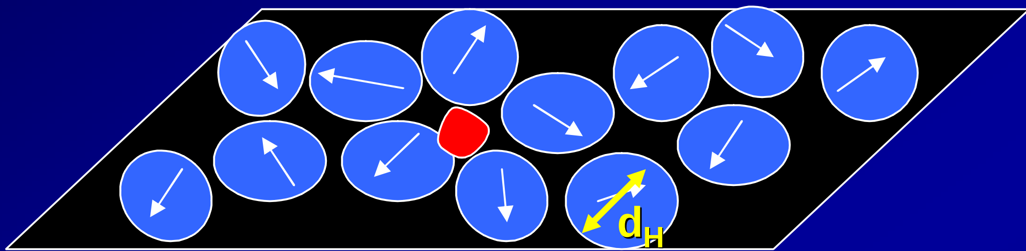
- *Cosmic strings*: Line-like concentrations of energy arising as topological defects in cosmological phase transitions.

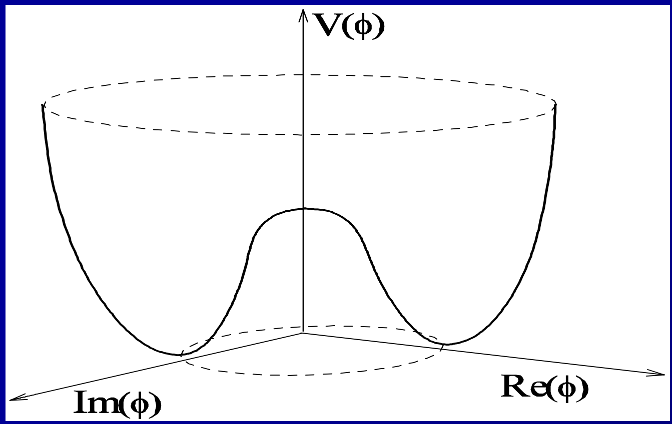
- *Example*: Complex scalar field with mexican hat potential



Kibble Mechanism: 2D Example

Vortex Formation

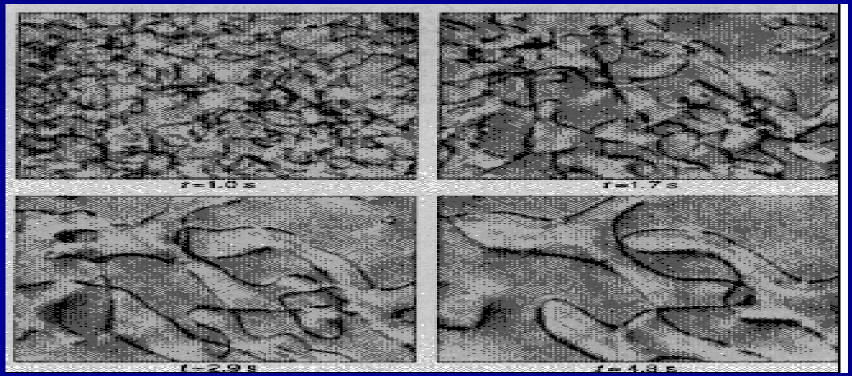




Kibble Mechanism: Any topologically allowed defect will be cosmologically formed

Why Strings?

- Produced in Phase Transitions



- Until 1997:

Structure Formation

$$G\mu \approx 10^{-6} \approx \left(\frac{\Delta T}{T}\right)_{CMB}$$

Ruled out (Battye et al)

- Now:

String Theory, Brane Inflation (Quevedo et al 2001, Sarangi & Tye 2002)

Generically produced in SUSY GUTS (Jeanerot et al 2003)

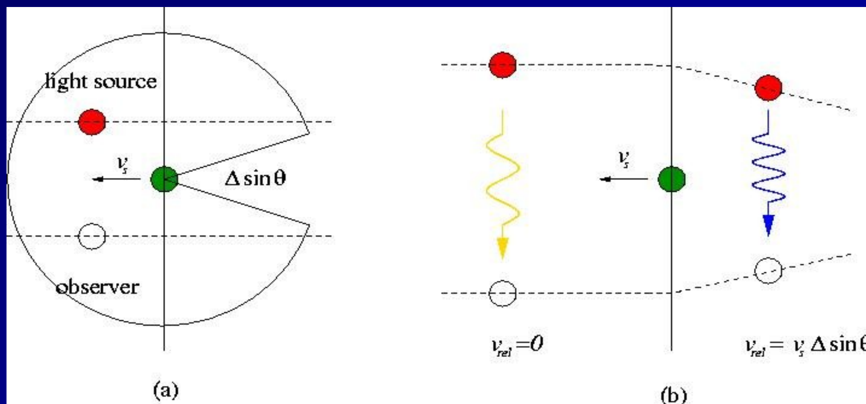
Observational: ~~CSL1~~, Oscillating Loop

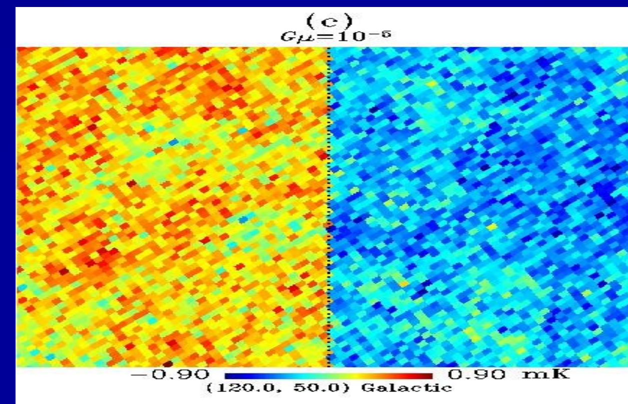
(Arguably) favoured by CMB

(Bevis, Hindmarsh, Kunz & Urrestilla, astro-ph/0702223)

String Gravity & Cusps

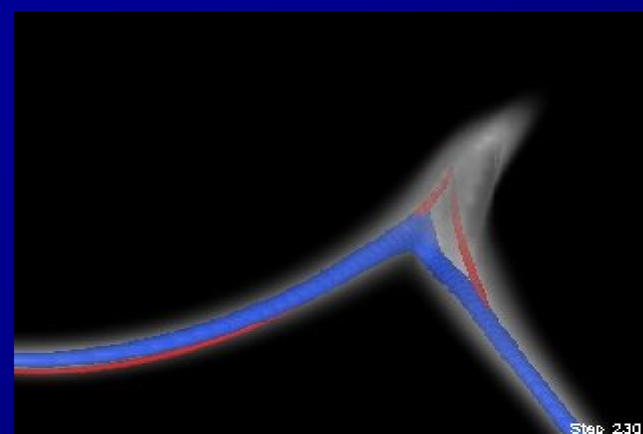
- ***String Gravity***: (Vilenkin 1981, Gott 1985)





(Kaiser & Stebbins 1984)

- ***Radiation from Cusps***:
  (Brandenberger 1987
  Bhattacharjee 1989
  Damour & Vilenkin 2001)



Astrophysical Consequences
(Berezinsky et al 1998, Vachaspati 2008)

(Potential) Observational Effects

- *CMB*: a) Discontinuous Doppler Shift by strings at "present" time (Kaiser-Stebbins effect)
  b) Fluctuations at surface of last scattering
  c) Sachs-Wolf effect, gravitational waves,…

  B-mode polarization (Pogosian et al 2006, 2007)
  No degeneracy with primordial tensors (Urestilla et al 2008)

- *Gravitational Lensing*: Double Images (no distortion)
  Microlensing (Kuijken et al 2007)

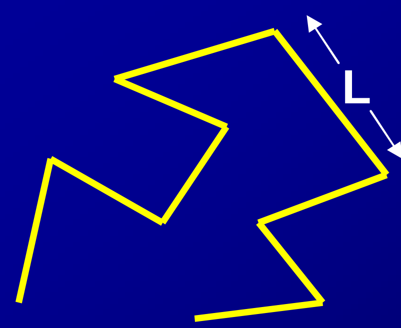
- *Gravitational Radiation*:
  a) Stochastic Background from loops (pulsar timing)
  b) Gravitational Waves from Cusps (LIGO,LISA)
  (Damour & Vilenkin 2000, 2001, 2005)

String Evolution

- Field Theory Simulations
- Nambu Strings → Simulations
  → Macroscopic approach

String network is Brownian

Characterised by correlation length L



Define energy density $\rho = \frac{\mu L}{L^3} = \frac{\mu}{L^2}$

$$\dot{\rho} \approx -2H\rho - \rho / L$$

ρ / L → loop production

Find *scaling solution* $L \sim t$

(Kibble 1985)

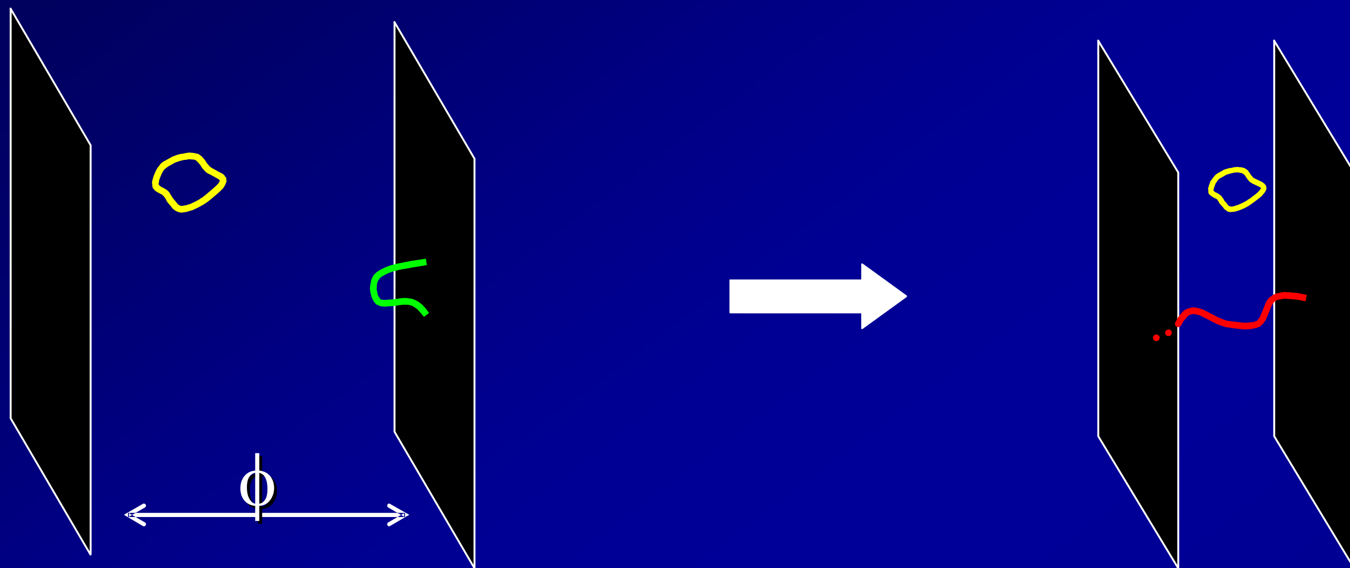
Nambu-Goto Simulation

(Martins & Shellard)

Analytic Models

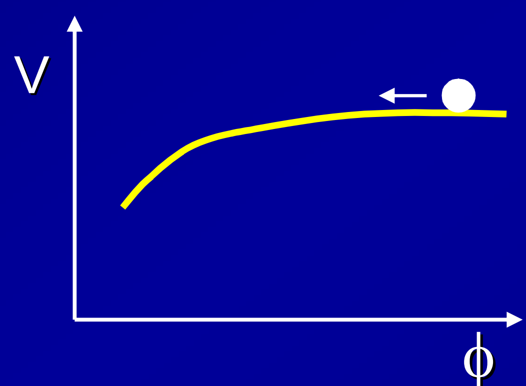
- Improved One-Scale Model (Bennett 1986)
- Kink-Counting Model (Allen & Caldwell 1990; Austin 1993)
- Functional Approach (Embacher 1992)
- Three-Scale Model (Austin, Copeland & Kibble 1993)
- Wiggly Model (Martins 1997)
- Velocity Dependent One-Scale (VOS) Model (Martins & Shellard 1996/2000)

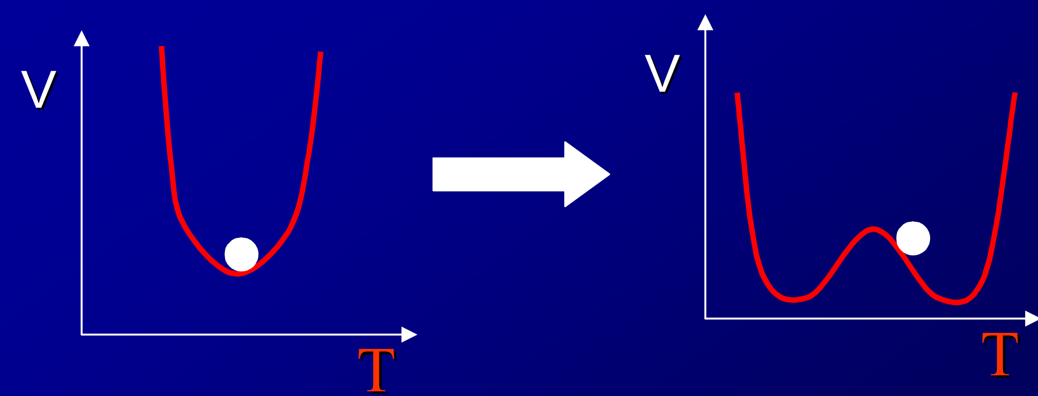
Brane Inflation



$$V_{\text{int}}(\phi) \approx -\frac{c}{\phi^{d-2}}$$

$$M^2(\phi) \approx M_s^2\left(\frac{\phi}{\phi_c} - 1\right)$$

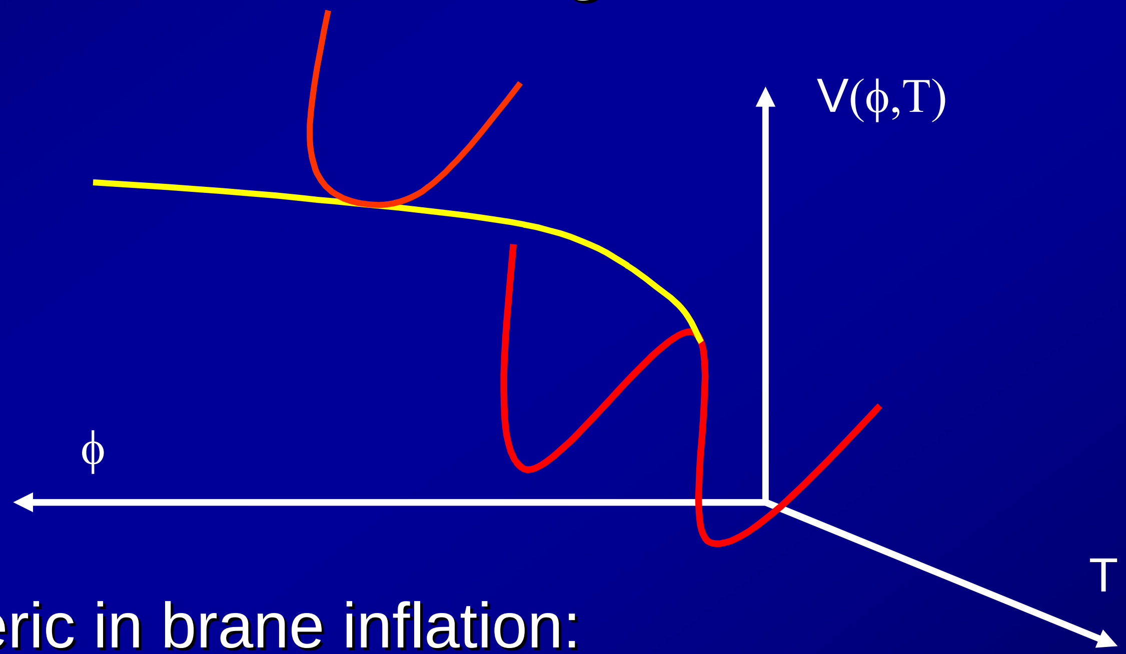




Relic String Defects

Brane inflation ends with tachyon condensation, producing a network of F & D strings.

(BMNQRZ 2001,
Sarangi & Tye 2002,
Dvali & Vilenkin 2004)



This seems to be generic in brane inflation:

- Brane-Antibrane (BMNQRZ 2001, KKLMMT, 2004)
- Branes at angles (Garcia-Bellido, Rabadan & Zamora 2001, Gomez-Reino & Zavala 2004)
- D3/D7 (Dasgupta, Herdeiro, Hirano, Kallosh 2002)
- Wilson Line Inflation (AA, Cremades & Quevedo 2004)

Strings in Extra Dimensions

Strings can miss in D>3 spatial dimensions

Introduces a probability for intercommuting P<1

(Jones, Stoica & Tye 2003)

$$\dot{\rho} \approx -2H\rho - \rho P / L$$

Scaling Solution:

$$\rho \propto P^{-2}$$

- Would lead to a much denser string network
- P<1 also enhances gravitational radiation

(Damour & Vilenkin 2005)

The EDVOS Model 1: Microscopic Equations

- Metric $\mathrm{d}s^2 = N(t)^2\mathrm{d}t^2 - a(t)^2\mathrm{d}\mathbf{x}^2 - b(t)^2\mathrm{d}\mathbf{l}^2$
- Nambu-Goto Action $S = -\mu\int\sqrt{-\gamma}\,\mathrm{d}^2\sigma$
- Equations of motion

$$\dot{\varepsilon} = -N^{-2}\varepsilon\left\{N\dot{N} + a\dot{a}\left[\dot{\mathbf{x}}^2 - \left(\frac{\mathbf{x}'}{\varepsilon}\right)^2\right] + b\dot{b}\left[\dot{\mathbf{l}}^2 - \left(\frac{\mathbf{l}'}{\varepsilon}\right)^2\right]\right\}$$

$$\ddot{\mathbf{x}} + \left\{2\frac{\dot{a}}{a} - N^{-2}\left\{N\dot{N} + a\dot{a}\left[\dot{\mathbf{x}}^2 - \left(\frac{\mathbf{x}'}{\varepsilon}\right)^2\right] + b\dot{b}\left[\dot{\mathbf{l}}^2 - \left(\frac{\mathbf{l}'}{\varepsilon}\right)^2\right]\right\}\right\}\dot{\mathbf{x}} = \left(\frac{\mathbf{x}'}{\varepsilon}\right)\varepsilon^{-1}$$

$$\ddot{\mathbf{l}} + \left\{2\frac{\dot{b}}{b} - N^{-2}\left\{N\dot{N} + a\dot{a}\left[\dot{\mathbf{x}}^2 - \left(\frac{\mathbf{x}'}{\varepsilon}\right)^2\right] + b\dot{b}\left[\dot{\mathbf{l}}^2 - \left(\frac{\mathbf{l}'}{\varepsilon}\right)^2\right]\right\}\right\}\dot{\mathbf{l}} = \left(\frac{\mathbf{l}'}{\varepsilon}\right)\varepsilon^{-1}$$

- Energy-Momentum Tensor & Energy

$$T^{\mu\nu} = \frac{1}{Na^3b^{D-3}}\mu\int\mathrm{d}\sigma\left(\varepsilon\dot{x}^\mu\dot{x}^\nu - \varepsilon^{-1}x'^\mu x'^\nu\right)\delta^{(D)}\left(\mathbf{x}-\mathbf{x}(\sigma,t),\mathbf{l}-\mathbf{l}(\sigma,t)\right)$$

$$E(t) = \int_{t=const}\sqrt{h}\,n_\mu n_\nu T^{\mu\nu}\,\mathrm{d}^3\mathbf{x}\,\mathrm{d}^{D-3}\mathbf{l} = N(t)\mu\int\varepsilon\,\mathrm{d}\sigma$$

The EDVOS Model 2: Macroscopic Equations

- Energy Density (equiv. correlation length L)

$$2\frac{\mathrm{d}L}{\mathrm{d}t} = \left[\left(2+w_l^{2}\right) + \left(2-w_l^{2}\right) v_x^2 + \left(1-w_l^{2}\right) v_l^2\right] HL + cP_{eff} v_x$$

Modify 3D terms

New term due to extra dimensional velocities

- String Velocities

$$v_x \frac{\mathrm{d}v_x}{\mathrm{d}t} = \frac{k_x v_x}{L}\left(1-v^2\right) - \left(2-w_l^{2}\right) H v_x^2 \left(1-v^2\right) - H v_x^2 v_l^2$$

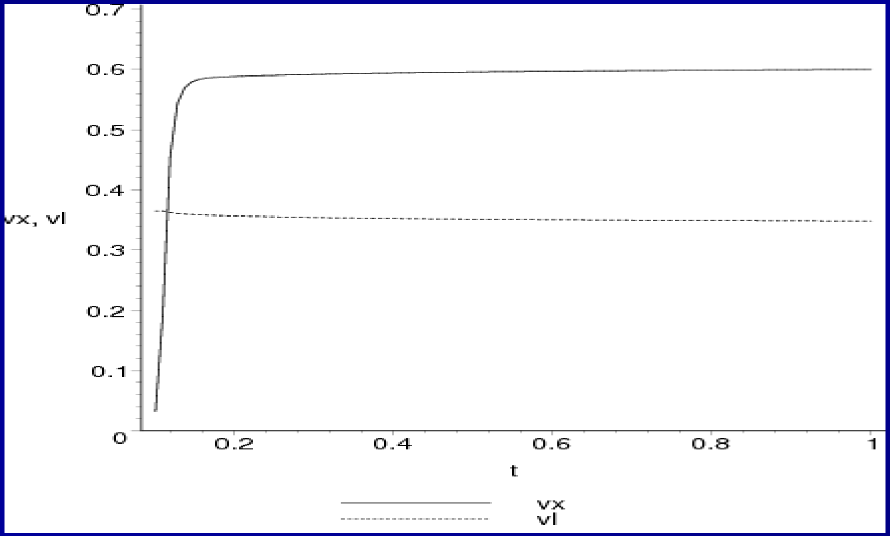
$$v_l \frac{\mathrm{d}v_l}{\mathrm{d}t} = \frac{k_l v_l}{L}\left(1-v^2\right) - \left(1-w_l^{2}\right) H v_l^2 \left(1-v^2\right) + H v_l^2 v_x^2$$

Effective 3D string motion slows down due to extra dimensional velocities

(AA & Shellard 2004)

The EDVOS Model 2: Macroscopic Equations

$$2\frac{\mathrm{d}L}{\mathrm{d}t} = \left[\left(2+w_l^{\,2}\right) + \left(2-w_l^{\,2}\right) v_x^2 + \left(1-w_l^{\,2}\right) v_l^2\right] HL \; + \; cP_{eff}v_x$$



$$v_x^2 + v_l^2 \leq 1/2$$

$$v_x\frac{\mathrm{d}v_x}{\mathrm{d}t} = \frac{k_x v_x}{L}\left(1-v^2\right) - \left(2-w_l^{\,2}\right)Hv_x^2\left(1-v^2\right) - Hv_x^2 v_l^2$$

$$v_l\frac{\mathrm{d}v_l}{\mathrm{d}t} = \frac{k_l v_l}{L}\left(1-v^2\right) - \left(1-w_l^{\,2}\right)Hv_l^2\left(1-v^2\right) + Hv_l^2 v_x^2$$

Intercommuting Probability

- Jackson, Jones & Polchinski 2004: $0.001 < P < 1$

  +Kinematic Constraints (Copeland, Kibble & Steer 2006, Salmi et al 2007)

- Effect of Small-Scale Structure. Need simulations.

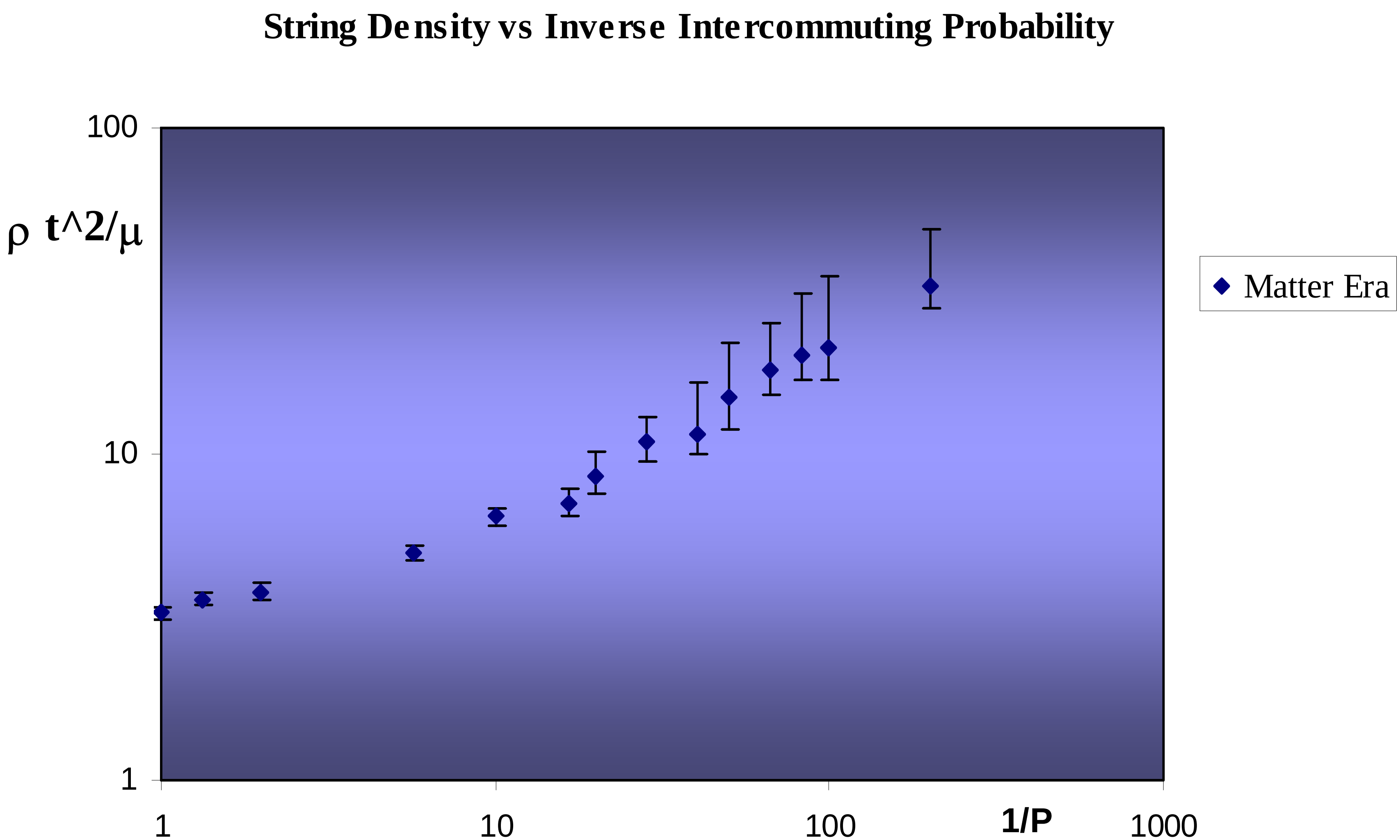
- Sakellariadou 2004: Flat space simulations with P<1 suggest $\rho \propto P^{-1}$

- Simulations in expanding space: $\rho \propto P^{-0.6\pm0.1}$

  (AA & Shellard 2005)

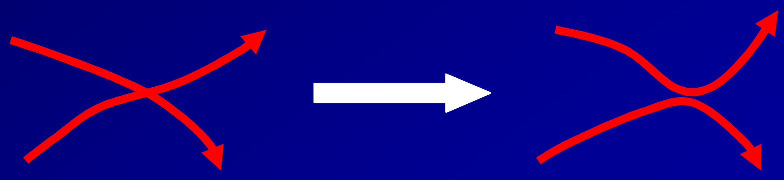
  Cf Vanchurin 2007 $\rho \propto P^{-2/3}$

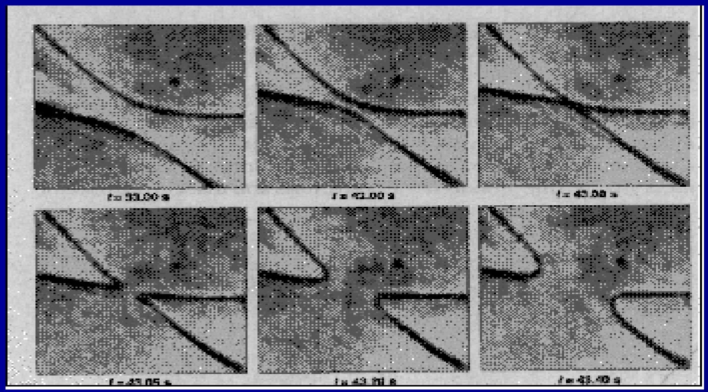
Numerical Results (AA & Shellard 2005)



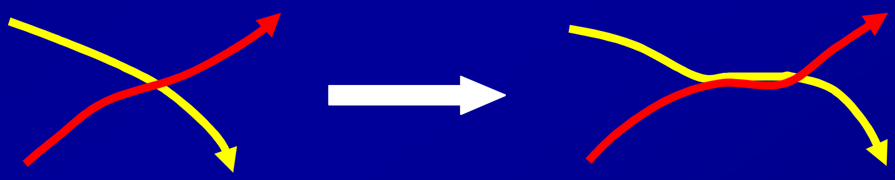
String Junctions

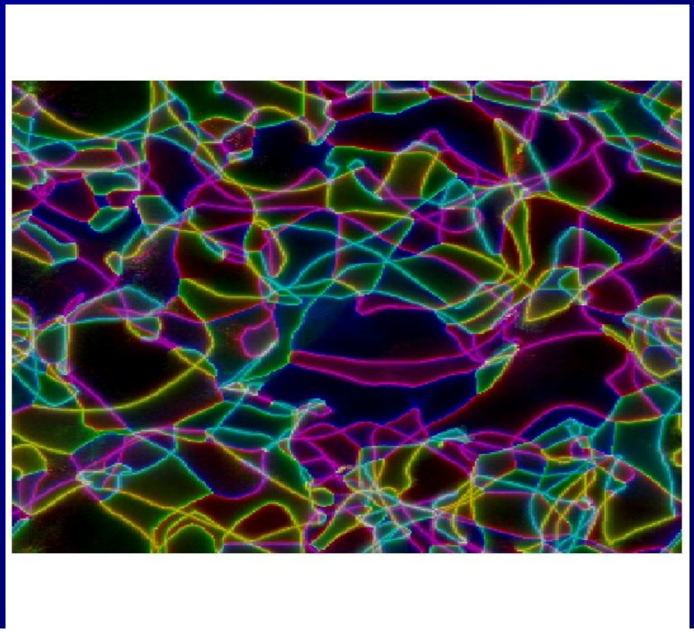
- Usual field theory strings interact by exchange of partners (P~1)





- F and D strings can bind together to form F-D composites





Cf. Non-Abelian Strings

Scaling?

- Copeland & Saffin, 2005: Numerical evidence for scaling in field theory model.

  Also Hindmarsh & Saffin, 2006

- Tye, Wasserman & Wyman, 2005: Multi-tension VOS model for entangled string network. Evidence for scaling.

- AA & Shellard, 2006: Non-Abelian Velocity-Dependent One-Scale Model (NAVOS) for networks with junctions.

NAVOS: Macroscopic Equations

- String Densities:

$$\dot{\rho}_i = -2\frac{\dot{a}}{a}(1-2v_i^{\,2})\rho_i - \frac{c_i v_i \rho_i}{L_i} - \sum_{a,k} \frac{d_{ia}^k \tilde{v}_{ia} l_{ia}^k(t)}{L_a^2 L_i^2} + \sum_{b,a\le b} \frac{d_{ab}^i \tilde{v}_{ab} l_{ab}^i(t)}{L_a^2 L_b^2}$$

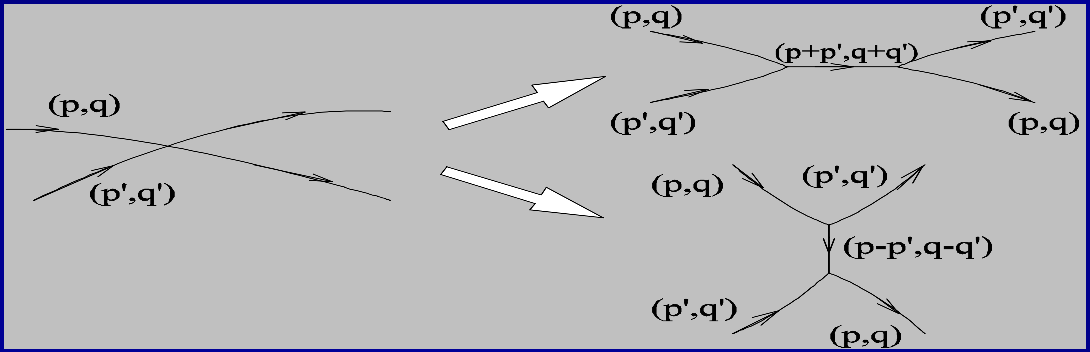
- String Velocities:

$$\dot{v}_i = (1-v_i^{\,2})\left[\frac{k_i}{L_i} - 2\frac{\dot{a}}{a}v_i + \sum_{b,a\le b} d_{ab}^i \frac{\tilde{v}_{ab}}{v_i} \frac{\left(\mu_a + \mu_b - \mu_i\right)}{\mu_i} \frac{l_{ab}^i(t) L_i^2}{L_a^2 L_b^2}\right]$$

where $l_{ij}^k(t)$ are model dependent $f(L_i, v_i, \mu_i)$
and c_i, d_{ij}^k are free parameters.

Cosmic Superstrings

- For (p,q)-strings zipping interactions must be included:

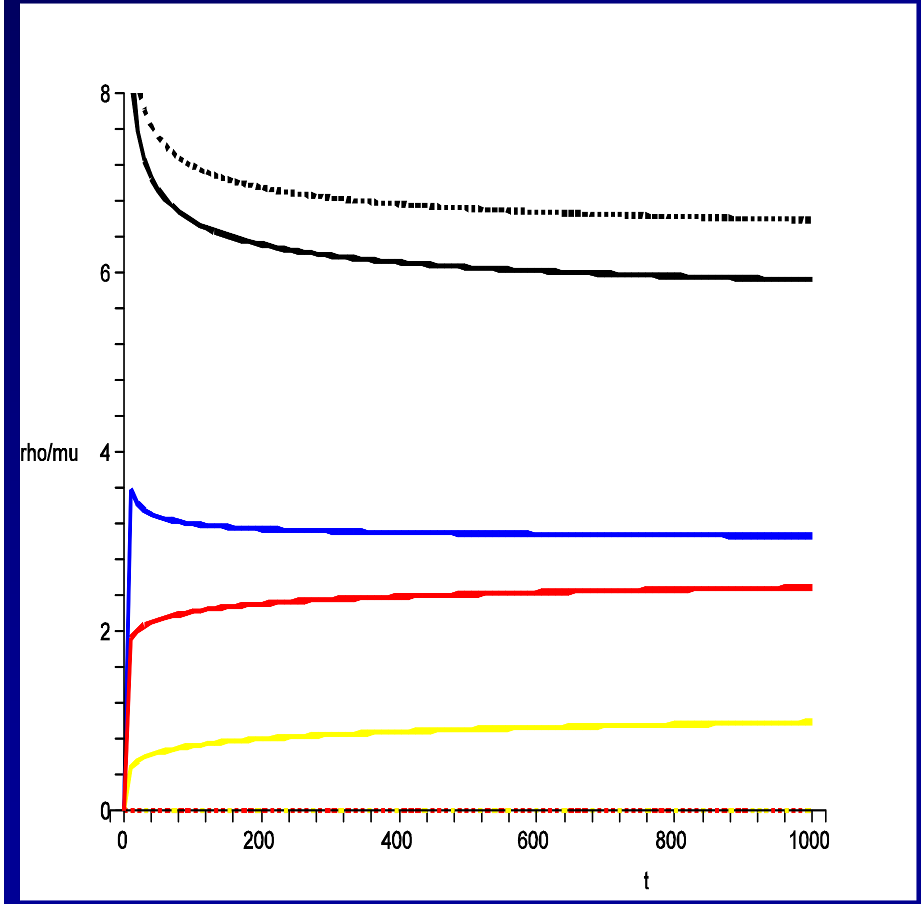


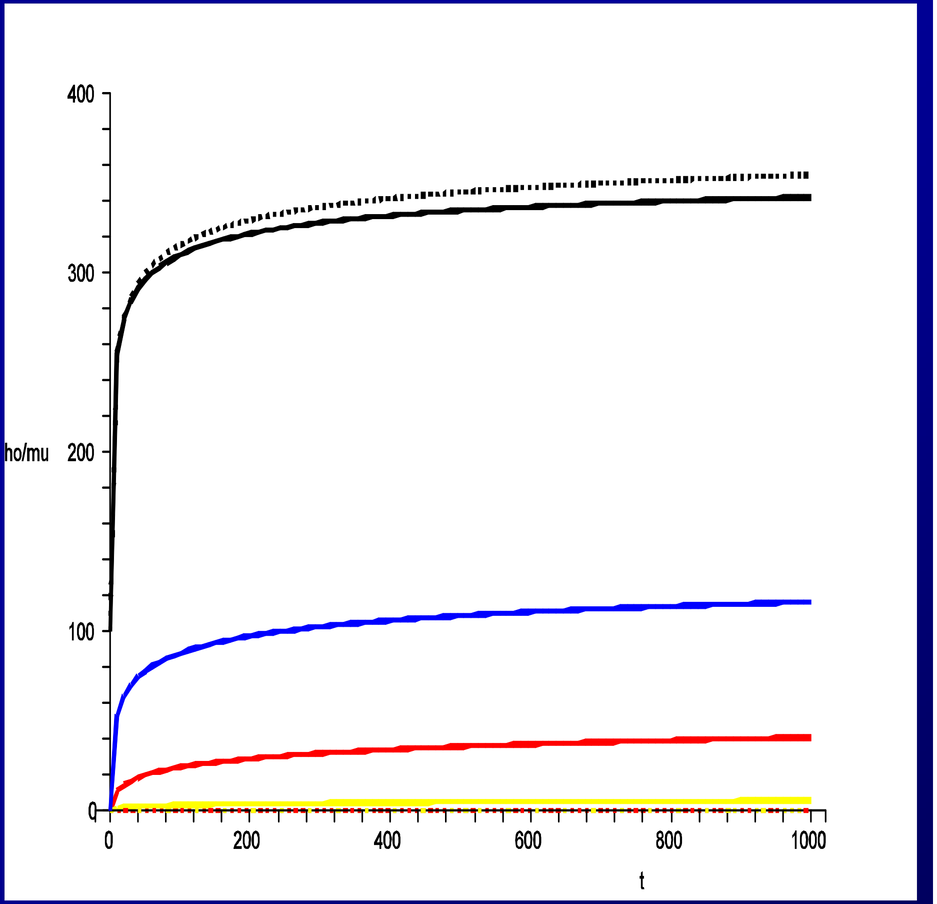
- Probability of additive/subtractive process is:

$$P^{\pm}_{(p,q)(p',q')} = \frac{1}{2}\left[1 \mp \left(\frac{pp'g_s^2 + qq'}{\left(p^2 g_s^2 + q^2\right)^{1/2}\left(p'^2 g_s^2 + q'^2\right)^{1/2}}\right)\right]$$

(Tye et al 2005)

Scaling Results





P=1

P<<1

Cosmological Constraints

Observational Bounds on Cosmic Strings:

$G\mu < 6\times10^{-7}$ CMB

(Wyman et al 2005)

$G\mu < 5\times10^{-8}$ Pulsar Timing

(Kaspi et al 1994, Mc Hugh et al 1996)

Impose constraints on stringy parameters:

String Scale, Compactification Radii, Warping, String coupling,…

DEGENERACIES

Degeneracies could be broken using other constraints:

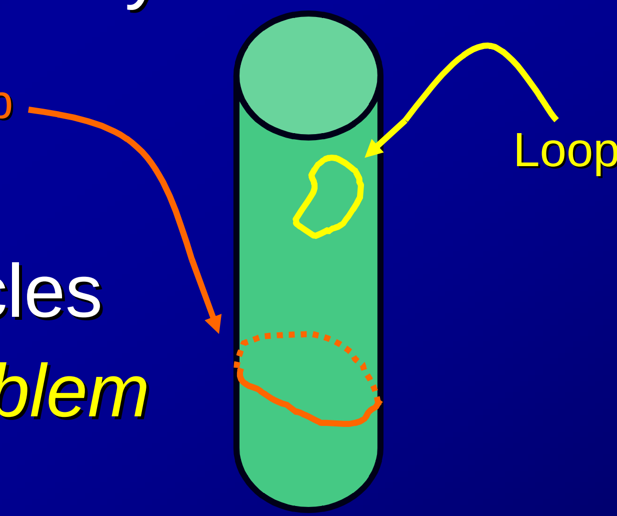
CMB, Non-Gaussianity, Gravitational Waves

(Lorenz, Martin & Ringeval, 2007)

More Stringy Constraints

<u>Example</u>: Cycloops (AA & Shellard 2005)

If internal manifold admits non-trivial 1-cycles then loops can be trapped



Cycloops behave like massive particles from 3D point of view *Monopole Problem*

Imposes stringent constrains on energy scale of inflation

<u>Other examples</u>: Dilaton emission (Babichev et al 2005)

Vortons (Brax et al 2006)

Outlook & Open Questions

- Cosmic Strings provide a potential observational window into HEP
- Already constraining stringy parameters but need better quantitative understanding
- Some Open Problems:
  - Small-Scale Structure (Martins & Shellard 2005, Rocha & Polchinski 2006, Sakelariadou et al, Vanchurin et al)
  - Number of kinks in loops
  - Networks with Junctions: Scaling?
  - Non-Gaussianity